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A normalised framework for the Zero Emissions Commitment

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S1 Supplementary material

The Supplementary material includes:

Text describing the ensemble set for the observationally-constrained, efficient Earth system model WASP;

Table S1 displays ranges for the input parameters making up the large ensemble used in WASP for the 1pctCO2 and flat10 experiments;

Tables S2 and S3 displays the diagnostics for the large ensemble using WASP for the 1pctCO2 and flat10 experiments;

Figures S1 and S2 displays the climate and carbon variables for a large ensemble following the 1pctCO2 and flat10 experiments for up to 300 years after net zero for WASP, including the median response and shading for the 5% to 95% spread in the ensembles.

S1.1 Ensembles for WASP

WASP includes a large set of ensembles to span parameter space, which are constructed by varying key variables within prescribed bounds (Supplementary Table S1). WASP ensemble members include perturbations in the three land carbon coefficients for the CO_2 fertilisation, net primary production-temperature relationship and soil carbon residence timescale (Goodwin, 2016) and the ocean deep box timescales (Supplementary Table S1), leading to significant differences in the carbon cycle responses. Other model parameters varied between the prior ensemble members include climate feedbacks, separated into Planck, fast and multi-decadal feedbacks (Goodwin, 2021), and parameters relating to how changes in atmospheric constituents induce radiative forcing (Goodwin and Cael, 2021). The observational consistency tests used to extract the final posterior ensemble are as described in Goodwin (2021), with the land carbon consistency tests as in Goodwin (2018).

Table S1. Parameters varied in the WASP prior ensemble and their distributions. The distributions are: U - uniform distribution with minimum and maximum range specified; N – normal distribution with mean and standard deviation stated; LN – lognormal distribution with mean and variance of the underlying normal distribution stated; SN – skew normal distribution with mean, standard deviation and skew parameter stated. The land carbon cycle parameters and distributions ($\partial NPP/\partial T$, γ_k and $\partial\tau_{soil}/\partial T$) are as described in Goodwin (2016). The climate feedback parameters and their distributions (λ_P, λ_f and λ_{md}) are as described in Goodwin (2021). All other parameters are as described in Goodwin and Cael (2021).

Parameter	Symbol	Units	Range
Sensitivity of net primary productivity (NPP) to temperature	$\partial NPP/\partial T$	PgC yr^{-1}K^{-1}	U(-5 to+1)
CO_2 fertilisation coefficient	γ_k		U(0 to 1)
Sensitivity of soil carbon residence timescale to temperature	$\partial\tau_{soil}/\partial T$	yr K^{-1}	U(-1.36 to 0.45)
Planck climate feedback	λ_P	W m^{-2}K^{-1}	$LN\left(\ln 3.3, \ln(1+0.1^2/3.3^2)\right)$
Fast climate feedbacks	λ_f	W m^{-2}K^{-1}	$LN\left(\ln\lambda_P, \ln 2)\right) - \lambda_P$
Multidecadal climate feedbacks	λ_{md}	W m^{-2}K^{-1}	$LN\left(\ln(\lambda_P+\lambda_f), \ln 2)\right) - (\lambda_P+\lambda_f)$
Ratio of SST change to global mean surface temperature at equilibrium			U(0.2 to 1.5)
Ratio of deep ocean T to SST change at equilibrium			U(0.1 to 1.0)
Timescale for fast climate feedbacks	τ_{fast}	days	N(8.9, 0.4)
Timescale for multidecadal climate feedbacks (pattern effect)	τ_{md}	years	U(20 to 45)
Timescale for surface ocean mixed layer to equilibrate with atmospheric chemistry	τ_{mixed}	years	U(0.5 to 1.0)
Timescale for upper ocean to equilibrate with surface ocean mixed layer	τ_{upper}	years	U(20 to 80)
Timescale for intermediate ocean to equilibrate with surface ocean mixed layer	τ_{inter}	years	U(150 to 1000)
Timescale for deep ocean to equilibrate with surface ocean mixed layer	τ_{deep}	years	U(500 to 1500)
Timescale for bottom ocean to equilibrate with surface ocean mixed layer	τ_{bottom}	years	U(1000 to 2500)
Radiative forcing coefficient for CO_2	a_{CO2}	W m^{-2}	N(5.35, 0.27)
Dimensionless uncertainty in CH_4 radiative forcing			N(1.0, 0.07)
Dimensionless uncertainty in N_2O radiative forcing			N(1.0, 0.05)
Dimensionless uncertainty in halocarbon radiative forcing			N(1.0, 0.05)
Direct radiative forcing from SO_x aerosols in 2010	$\gamma_{aero:SOx}$	W m^{-2}	N(-0.31, 0.11)
Direct radiative forcing from black carbon aerosols in 2010	$\gamma_{aero:BC}$	W m^{-2}	N(0.18, 0.07)
Direct radiative forcing from organic carbon aerosols in 2010	$\gamma_{aero:OC}$	W m^{-2}	N(-0.03, 0.01)
Direct radiative forcing from NMVOC aerosols in 2010	$\gamma_{aero:NMVOC}$	W m^{-2}	N(-0.06, 0.09)
Direct radiative forcing from NO_x aerosols in 2010	$\gamma_{aero:NOX}$	W m^{-2}	N(-0.08, 0.04)
Direct radiative forcing from NH_3 aerosols in 2010	$\gamma_{aero:NH3}$	W m^{-2}	N(-0.08, 0.04)
Indirect radiative forcing from aerosols in 2010	$R_{aci:2010}$	W m^{-2}	SN(-0.55, 0.37,-2.0)
Radiative forcing coefficient for volcanic aerosols		W m^{-2}	N(-10, 0.5)

Table S2. Climate model response for the large ensemble, WASP for climate and carbon variables following a 1pctCO2 experiment with a cumulative carbon emission of 1000 PgC. Quantities given are the median, 5th percentile and 95th percentile at years 50, 100 and 400 after net zero.

	t'	50 years	100 years	400 years
(a) temperature changes				
temperature rise	ΔT (K)	1.09 (0.77 to 1.77)	1.10 (0.71 to 2.14)	0.98 (0.60 to 2.54)
ZEC	$\Delta T(t) - \Delta T(t_{ZE})$ (K)	-0.10 (-0.47 to 0.43)	-0.09 (-0.56 to 0.82)	-0.22 (-0.71 to 1.19)
geometric ZEC	$\Delta T(t)/\Delta T(t_{ZE})$	0.92 (0.63 to 1.36)	0.92 (0.57 to 1.66)	0.82 (0.47 to 1.96)
(b) carbon inventory changes				
atmospheric carbon	ΔI_A (PgC)	310 (252 to 396)	288 (235 to 374)	226 (189 to 301)
land carbon	ΔI_L (PgC)	371 (219 to 476)	333 (177 to 435)	252 (80 to 349)
ocean carbon	ΔI_O (PgC)	320 (262 to 399)	380 (316 to 465)	522 (453 to 629)
(c) radiative balance				
radiative forcing	ΔF (Wm^{-2})	2.26 (1.87 to 2.80)	2.14 (1.76 to 2.66)	1.74 (1.46 to 2.23)
radiative response	$-\Delta R$ (Wm^{-2})	1.89 (1.52 to 2.35)	1.84 (1.50 to 2.25)	1.66 (1.40 to 2.05)
planetary heat uptake	ΔN (Wm^{-2})	0.35 (0.15 to 0.73)	0.25 (0.08 to 0.68)	0.07 (0.03 to 0.26)
(d) normalised contributions to ZEC				
thermal contribution	Normalised $\Delta T/\Delta F$	1.28 (0.94 to 1.77)	1.37 (0.91 to 2.17)	1.50 (0.92 to 2.92)
radiative contribution	Normalised $\Delta F/\Delta I_A$	1.09 (1.06 to 1.11)	1.11 (1.07 to 1.13)	1.15 (1.10 to 1.19)
carbon contribution	Normalised ΔI_A	0.66 (0.60 to 0.74)	0.60 (0.55 to 0.74)	0.47 (0.43 to 0.62)
(e) Normalised thermal components				
Radiative response fraction	Normalised $1 - \Delta N/\Delta F$	1.11 (0.97 to 1.28)	1.15 (0.98 to 1.33)	1.26 (1.15 to 1.40)
Inverse climate feedback	Normalised λ^{-1}	1.15 (0.77 to 1.79)	1.18 (0.73 to 2.18)	1.19 (0.72 to 2.45)
(f) Partition of emissions				
Airborne fraction	$\Delta I_A(t)/I_{em}$	0.31 (0.25 to 0.40)	0.29 (0.24 to 0.37)	0.23 (0.19 to 0.30)
Landborne fraction	$\Delta I_L(t)/I_{em}$	0.37 (0.22 to 0.48)	0.33 (0.18 to 0.44)	0.25 (0.08 to 0.35)
Oceanborne fraction	$\Delta I_O(t)/I_{em}$	0.32 (0.26 to 0.40)	0.38 (0.32 to 0.46)	0.52 (0.45 to 0.63)

Table S3. Climate model response for the large ensemble, WASP for climate and carbon variables following a flat10 experiment with a cumulative carbon emission of 1000 PgC. Quantities given are the median, 5th percentile and 95th percentile at years 50, 100 and 400 after net zero.

	t'	50 years	100 years	400 years
(a) temperature changes				
temperature rise	ΔT (K)	1.10 (0.73 to 1.92)	1.09 (0.69 to 2.24)	0.97 (0.59 to 2.53)
ZEC	$\Delta T(t) - \Delta T(t_{ZE})$ (K)	-0.06 (-0.25 to 0.41)	-0.07 (-0.31 to 0.73)	-0.19 (-0.46 to 1.02)
geometric ZEC	$\Delta T(t)/\Delta T(t_{ZE})$	0.95 (0.77 to 1.29)	0.94 (0.71 to 1.50)	0.83 (0.59 to 1.68)
(b) carbon inventory changes				
atmospheric carbon	ΔI_A (PgC)	299 (242 to 383)	280 (228 to 366)	224 (186 to 297)
land carbon	ΔI_L (PgC)	350 (199 to 455)	320 (159 to 421)	249 (78 to 345)
ocean carbon	ΔI_O (PgC)	349 (290 to 430)	399 (336 to 485)	527 (459 to 636)
(c) radiative balance				
radiative forcing	ΔF (Wm^{-2})	2.20 (1.81 to 2.73)	2.09 (1.71 to 2.61)	1.72 (1.44 to 2.21)
radiative response	$-\Delta R$ (Wm^{-2})	1.86 (1.51 to 2.28)	1.82 (1.50 to 2.23)	1.64 (1.39 to 2.03)
planetary heat uptake	ΔN (Wm^{-2})	0.30 (0.12 to 0.70)	0.22 (0.08 to 0.63)	0.07 (0.03 to 0.24)
(d) normalised contributions to ZEC				
thermal contribution	Normalised $\Delta T/\Delta F$	1.17 (0.98 to 1.48)	1.24 (0.97 to 1.75)	1.34 (0.98 to 2.24)
radiative contribution	Normalised $\Delta F/\Delta I_A$	1.06 (1.04 to 1.07)	1.07 (1.04 to 1.09)	1.10 (0.07 to 1.14)
carbon contribution	Normalised ΔI_A	0.77 (0.73 to 0.86)	0.71 (0.67 to 0.86)	0.57 (0.51 to 0.72)
(e) Normalised thermal components				
Radiative response fraction	Normalised $1 - \Delta N/\Delta F$	1.08 (0.98 to 1.15)	1.12 (1.00 to 1.19)	1.20 (1.13 to 1.29)
Inverse climate feedback	Normalised λ^{-1}	1.09 (0.87 to 1.53)	1.10 (0.84 to 1.73)	1.10 (0.83 to 1.83)
(f) Partition of emissions				
Airborne fraction	$\Delta I_A(t)/I_{em}$	0.30 (0.24 to 0.38)	0.28 (0.23 to 0.37)	0.22 (0.19 to 0.30)
Landborne fraction	$\Delta I_L(t)/I_{em}$	0.35 (0.20 to 0.46)	0.32 (0.16 to 0.42)	0.25 (0.08 to 0.35)
Oceanborne fraction	$\Delta I_O(t)/I_{em}$	0.35 (0.29 to 0.43)	0.40 (0.34 to 0.49)	0.53 (0.46 to 0.63)

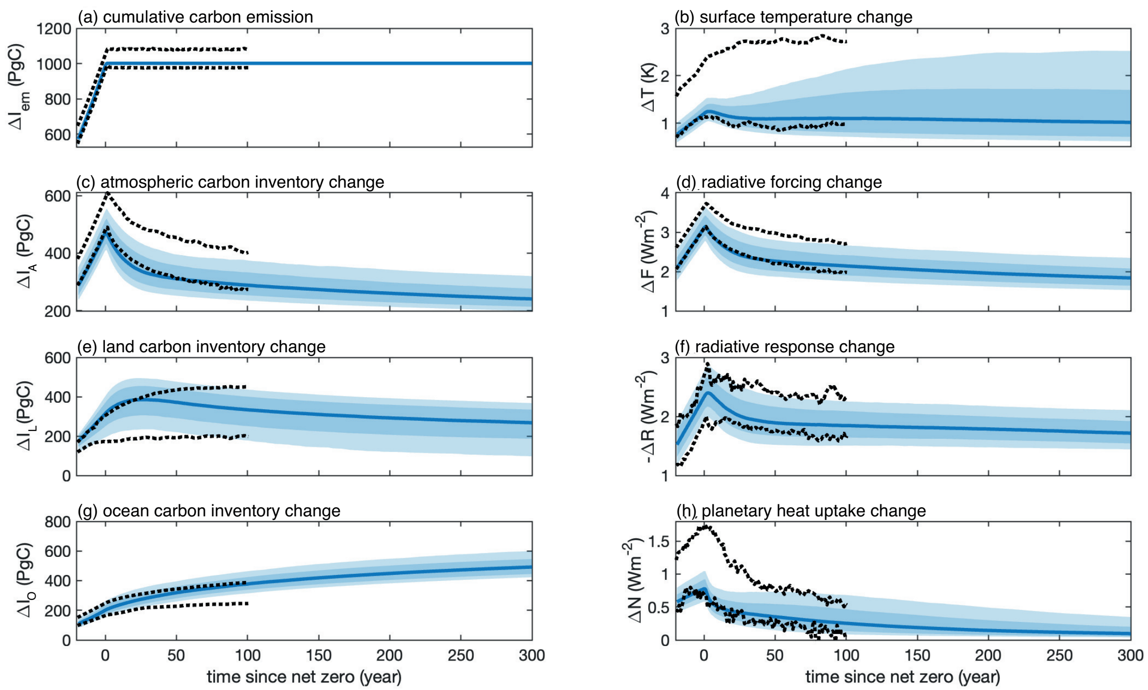

Figure S1. Temporal evolution of carbon and climate variables relative to the time of net zero (years) for the 1pctCO2 experiment from the WASP simulations, displaying median (blue line), 1-sigma range (dark shading) and 95% range (light shading) together with bounds from ZECMIP (black dashed line): (a) cumulative carbon emissions, $\Delta I_{em}(t')$ (PgC); (b) surface temperature change relative to the pre industrial, $\Delta T(t')$ (K); (c, e and g) the change in atmospheric carbon inventory, $\Delta I_A(t')$, land carbon inventory, $\Delta I_L(t')$ and ocean carbon inventory, $\Delta I_O(t')$, (all in PgC); and (d, f and h) the change in radiative forcing, $\Delta F(t')$, radiative response, $-\Delta R(t')$, and planetary heat uptake, $\Delta N(t')$ (all in W m^{-2}).

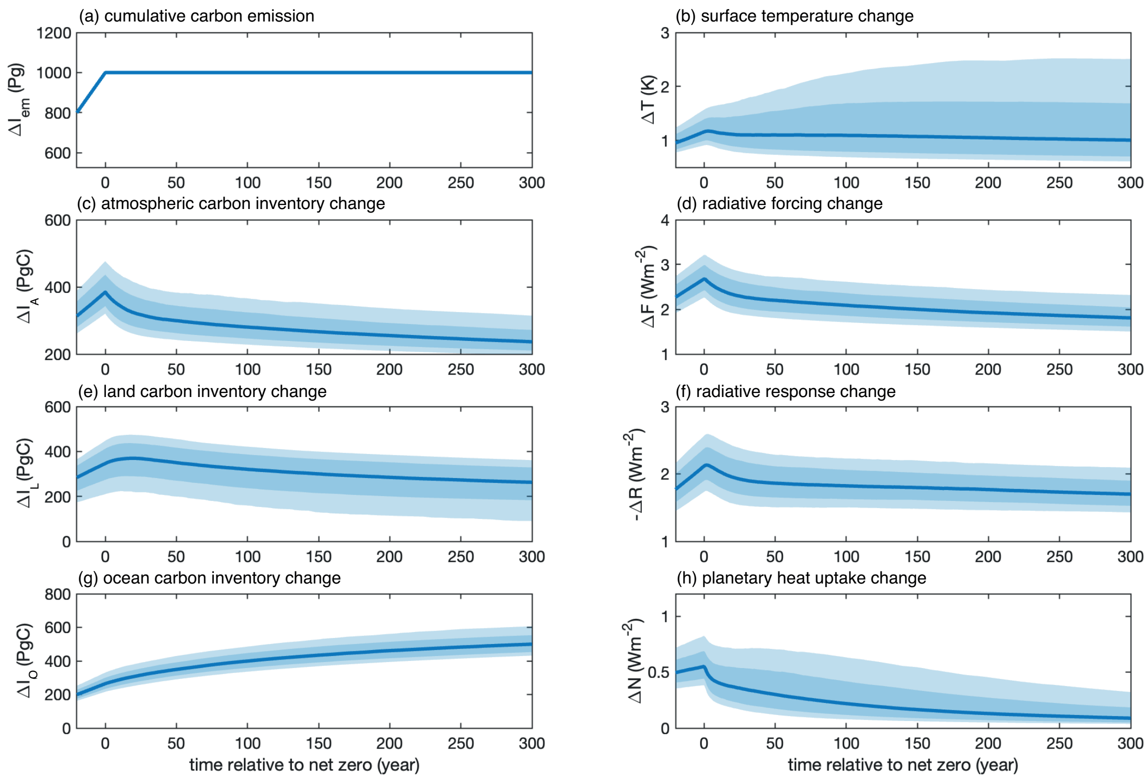

Figure S2. Temporal evolution of carbon and climate variables relative to the time of net zero (years) for the flat10 experiment from the WASP simulations: (a) cumulative carbon emissions, $\Delta I_{em}(t')$ (PgC); (b) surface temperature change relative to the pre industrial, $\Delta T(t')$ (K); (c, e and g) the change in atmospheric carbon inventory, $\Delta I_A(t')$, land carbon inventory, $\Delta I_L(t')$ and ocean carbon inventory, $\Delta I_O(t')$, (all in PgC); and (d, f and h) the change in radiative forcing, $\Delta F(t')$, radiative response, $-\Delta R(t')$, and planetary heat uptake, $\Delta N(t')$ (all in W m^{-2}).

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